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An Evaluation of Lime Residuals Management Alternatives for Water Utilities

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An Evaluation of Lime Residuals Management Alternatives for Water Utilities

by

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Abstract

An Evaluation of Lime Residuals Management Alternatives for Water Utilities

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In the United States, some utilities provide lime softening to remove hardness from the drinking water. Lime softening generates residuals as part of the water treatment process, which are inert and non-hazardous. This report provides an environmental and economic evaluation of three lime residuals disposal alternatives: a registered disposal site, beneficially reusing the lime residuals in cement manufacturing, and recalcinating the residuals to reduce the utility's lime dosage. This report also provides an overview of relevant non-economic factors utilities should consider when selecting a residuals management solution. Because the best alternative for any utility will be specific to that utility's resources, conditions, and values, this report serves as a framework others might use when evaluating their lime residuals management alternatives.

This report found the emissions due to recalcination and the emissions reduction from beneficially reusing the lime residuals in cement manufacturing are orders of magnitude larger than the transportation emissions associated with the registered disposal site. Notably, the emissions due to recalcination will likely be offset by a reduction in lime

production, but shifting the emissions from the private sector to a utility might be undesirable. Of the three alternatives, recalcination has the highest capital costs due to the need to purchase a rotary kiln. Cement manufacturing has the highest operations and maintenance costs, and recalcination presents a net savings in operations and maintenance costs due to the chemical savings associated with reduced lime usage. Overall, recalcination is the most financially attractive option, but cement manufacturing provides the most value when considering the social cost of carbon dioxide emissions. Utilities should also consider non-economic factors when assessing lime residuals disposal alternatives, including public perception, managerial impacts, regulatory requirements, and the utility's values and organizational structure, to assess the full impacts of the alternatives and maximize the likelihood of the selected alternative receiving approval by the public and the utility's governing body.

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Chapter 1: Introduction

BACKGROUND

Hard water is water with high mineral content (specifically calcium, magnesium, and other polyvalent cations), and it is a common problem in the United States. Although hard water is not a health risk, it can cause mineral buildup, leading to spots on otherwise clean dishes, mineral deposits in showers and shower heads, as well as scale buildup in pipes, hot water heaters, boilers, and cooling towers, and other annoyances. Water customers struggling with hard water can install household or industrial water softeners. Some utilities include softening as part of their water treatment process to protect their distribution systems and reduce the burden on their customers.

Common hard water treatment techniques include ion exchange, reverse osmosis, and lime softening. Ion exchange and reverse osmosis are used in home water softeners and at small water treatment plants (WTPs). Larger water utilities, such as Austin Water[1], use lime softening as a cost-effective means of softening large volumes of water. Utilities using lime softening at their water treatment plants can either receive bulk deliveries of quicklime (CaO), which is slaked with water to produce a lime slurry solution (calcium hydroxide or $Ca(OH)_2$), or can purchase bulk deliveries of already slaked solution. The lime slurry is added to the water as part of the clarification process, raising the pH of the water and therefore driving the carbonate system to convert bicarbonate (HCO_3^-) to carbonate (CO_3^{2-}). The carbonate (CO_3^{2-}) reacts with the calcium (Ca^{2+}) already in the water, as well as the calcium added in the lime slurry, and precipitates calcium carbonate ($CaCO_3$) out of the water per the following reaction:

$$CO_3^{2-} + Ca^{2+} \rightarrow CaCO_3\ (s) \qquad \text{(Equation 1)}$$

[1] City of Austin. "Lead." Austin Water. http://www.austintexas.gov/page/lead.

The calcium carbonate is removed during the drinking water treatment process, along with other particles and contaminants, through the coagulation, flocculation, and sedimentation processes. Adding a chemical coagulant to the water de-stabilizes the particles in the water by neutralizing their charge (coagulation). The destabilized particles precipitate out of the water and come together to form a floc (flocculation), which is heavier than the water and settles out (sedimentation). One industry approximation is that 2.0-2.5 pounds (lbs) of dry solids are removed from water through lime softening for every 1 pound of lime added.[2] As the waste stream is primarily calcium carbonate, it is referred to as lime residuals.

Disposal options for lime residuals vary across utilities. Common options include drying lagoons, dewatering and landfilling residuals, discharging residuals into the local sanitary sewer system, and land application in agricultural areas for pH adjustment of soils. As the author of this report is a student at The University of Texas at Austin, this report is focused on potential disposal alternatives in Central Texas. In Texas, any disposal alternative must comply with lime residuals disposal regulations set by the Texas Commission on Environmental Quality (TCEQ) and the Environmental Protection Agency (EPA).

This report explores the benefits and drawbacks associated with three disposal alternatives utilities might consider when evaluating how to manage their lime residuals, including one conventional option and two less explored options: a registered disposal site, beneficial reuse in cement manufacturing, and recalcination. This report assumes the registered disposal site is necessary to provide additional drying of the lime residuals for

[2] Unpublished information based on the author's experience.

either cement manufacturing or recalcination and therefore that the registered disposal site presents a base case for the other two alternatives.

The purpose of this report is to provide an environmental and economic evaluation of these three alternatives as well as an overview of relevant non-economic factors to compare the advantages and disadvantages of each alternative. As this report relies on a number of assumptions that will vary on a utility-by-utility basis, an equally important objective of this report is to provide a framework others might use when evaluating residuals management alternatives with their site-specific parameters and conditions.

REGISTERED DISPOSAL SITE

The first alternative, using a registered disposal site, is simple: A utility selects a location for its lime residuals disposal (preferably a site that has already been excavated), fills the excavated area with lime residuals, caps the area, and repurposes the site once it reaches its capacity. Unfortunately, given the large space requirements necessary to provide a long-term lime residuals disposal option, there are typically only a limited number of viable sites within close proximity to a utility. The TCEQ would need to approve any site for lime residuals disposal through the registration process per Title 30, Texas Administrative Code, Chapter 312, Subchapter F, "Disposal of Water Treatment Sludge."[3] The registration process requires a utility to identify the site and approximate the quantity of lime residuals to be disposed. Because lime residuals are inert, a liner is not necessary for the registered disposal site; requirements to protect nearby waters are general and

[3] 30 Tex. Admin. Code § 312.121-123 (2005).

focused on outcomes rather than providing specific restrictions.[4] These regulations are discussed in greater detail in Chapter 2: Environmental Evaluation.

Once a site has been approved and is in use, a utility would submit an annual report to the TCEQ, detailing the actual quantity of lime residuals disposed and providing laboratory test results to demonstrate compliance with permit limitations. This process is straightforward and unlikely to be cost-prohibitive; one such permit was issued as recently as 2015.[5] If an appropriate site can be acquired and permitted, filling an existing lime/gravel quarry involves a relatively low construction cost and minimal operations and maintenance (O&M) impact. However, a registered disposal site alone is a temporary solution; once the site is full, another site would need to be identified and acquired.

CEMENT MANUFACTURING

Cement manufacturing accounts for 5% of total carbon dioxide emissions worldwide.[6] Portland limestone cement (PLC) is becoming increasingly popular as a means of producing cement with reduced carbon dioxide (CO_2) emissions; PLC is manufactured by adding powdered limestone at the end of the manufacturing process as a partial replacement in cement, reducing raw material requirements in addition to reducing CO_2 emissions. Today, most cement manufacturers produce PLC using 3-5% powdered limestone; some manufacturers use powdered limestone at higher replacement rates of 5-

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[4] Linendoll, Chris. Unpublished Letter to Charles R. Maddox, May 21, 2015. Re: City of Austin - Austin Water Utility - Approval of Registration Number: 730010. Texas Commission on Environmental Quality, Austin, TX.
[5] Ibid.
[6] Rubenstein, Madeleine. "Emissions from the Cement Industry." State of the Planet - Climate. Last modified May 9, 2012. https://blogs.ei.columbia.edu/2012/05/09/emissions-from-the-cement-industry/.

15%.[7] While there is little evidence demonstrating the operational feasibility of reusing lime residuals in cement manufacturing, utilities are beginning to explore it as a viable alternative for lime residuals management.[8]

RECALCINATION

Recalcination is the process of re-heating the calcium carbonate to 1,010° Celsius[9] to convert it back to usable quicklime (CaO) per the following equation:

$$CaCO_3 + heat \rightarrow CaO + CO_2 \qquad \text{(Equation 2)}$$

Heating the lime residuals to such a high temperature typically requires a rotary lime kiln with an associated capital cost and spatial footprint in addition to being very energy intensive. Because rotary kilns are large and require a significant amount of energy to start up, they are typically operated as continuously as possible to maximize energy efficiency. Any recalcination site must have sufficient space to stockpile the lime residuals in addition to the space for the kiln itself. Recalcination would allow a utility to replace approximately 80% of its lime usage with recalcinated lime residuals[10], providing a large benefit by significantly reducing chemical costs. Any excess lime generated in the recalcination process could be an additional income source through sale to interested parties. Any rotary lime kiln would have to comply with federal and state regulations on air emissions.

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[7] Lute, Racheal, Thano Drimalas, and Kevin Folliard. "Beneficial Use of Lime Residuals in Industrial and Infrastructure Applications: A Feasibility Study." Unpublished manuscript, The University of Texas at Austin, Austin, TX, June 30, 2017. Page 9.

[8] D'Adamo, Peter. "Alternative Options for Beneficial Reuse of Solids." Speech, AWWA 2016 Water Quality Technology Conference & Exposition, Indianapolis, IN, November 16, 2016.

[9] Michel, Hani Emil. "Technical Memorandum No. 10: Residuals Management." Unpublished manuscript, Carollo Engineers, Austin, TX, December 2008. Page 10-8.

[10] Ibid.

While partnering with a local lime manufacturer would reduce a utility's capital costs associated with recalcination by eliminating the need for the utility to purchase its own kiln, such a partnership would be reliant on a strong and sustainable working relationship between parties. Recalcination can only be an effective as a long-term solution when a utility has easy access to a kiln; if a utility partnered with a local lime manufacturer that later went out of business, the utility would be left scrambling to find an immediate solution to deal with large lime residuals volumes being produced. A partnership would require a high level of confidence that the lime manufacturer would stay in business, perhaps as a long-term contract between the utility and the lime manufacturer to reduce risk to either party. Such a mutually beneficial long-term agreement might be difficult to execute.

Recalcination requires pre-treatment to remove magnesium from the lime residuals, which includes diluting the residuals, acidifying the residuals with CO_2 to dissolve the magnesium hydroxide, and then dewatering the residuals to remove the excess liquid.[11] As the extent of magnesium removal required will depend on the initial magnesium concentration in a utility's lime residuals, the impacts of magnesium pre-treatment are not included in this report.

Carbon dioxide (CO_2) is commonly used in the water treatment process following lime softening to reduce the pH of the water to a more acceptable level, at least partially offsetting the increased pH of the water due to the lime softening process. In Austin, the raw (untreated) water pH ranges from 7.9-8.3[12]. Lime is added to the water to raise the pH

[11] Ibid. Page 10-11.
[12] City of Austin Austin Water. *City of Austin Water Quality Summary: 3rd Quarter 2018*. 2018. http://www.austintexas.gov/sites/default/files/files/Water/WaterQualityReports /WQS_2018_3rd.pdf.

to approximately 10.1 as part of the softening process[13]. Then, carbon dioxide is used to adjust the pH back down to 9.6, which is the pH of the water as it enters the distribution system.[14] As the recalcination process also generates carbon dioxide, it is feasible to capture the carbon dioxide and use it in the water treatment process. The practicality of reusing carbon dioxide would be affected by the proximity of a utility's recalcination site to its water treatment plant(s); this report assumes capturing carbon dioxide is not economically viable.

[13] Unpublished information based on the author's experience.
[14] City of Austin Austin Water. *City of Austin Water Quality Summary: 3rd Quarter 2018*. 2018. http://www.austintexas.gov/sites/default/files/files/Water/WaterQualityReports /WQS_2018_3rd.pdf.

Chapter 2: Environmental Evaluation

This chapter evaluates environmental impacts associated with each alternative. Because water and soil pollution are not anticipated to result from any of the three alternatives, this report focuses on air pollution. As part of the Clean Air Act, the EPA is required to set National Ambient Air Quality Standards (NAAQS) for pollutants "considered harmful to public health and the environment."[15] Thus far, NAAQS have been set for sulfur dioxide, particulate matter, carbon monoxide, ozone, nitrogen dioxide, and lead, known as "criteria" air pollutants.[16]

The six criteria air pollutants are associated with a number of negative effects. Sulfur dioxide (SO_2) can cause acute respiratory effects and can harm the environment by damaging foliage, reducing plant growth, and contributing to acid rain.[17] Particulate matter (PM) small enough to penetrate into the deep lung can cause serious health effects.[18] Particulate matter is regulated based on particle size, and NAAQS are in place for particulate matter with a diameter less than 2.5 micrometers ($PM_{2.5}$) and for particulate matter with a diameter less than 10 micrometers (PM_{10}).[19] Carbon monoxide (CO) binds preferentially to hemoglobin in the blood; at high levels, carbon monoxide poisoning can cause dizziness or death.[20]

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[15] United States Environmental Protection Agency. "NAAQS Table." Criteria Air Pollutants. Last modified December 20, 2016. https://www.epa.gov/criteria-air-pollutants/naaqs-table.
[16] Ibid.
[17] United States Environmental Protection Agency. "Sulfur Dioxide Basics." Sulfur Dioxide Pollution. Last modified June 28, 2018. https://www.epa.gov/so2-pollution/sulfur-dioxide-basics.
[18] United States Environmental Protection Agency. "Particulate Matter (PM) Basics." Particulate Matter (PM) Pollution. Last modified November 14, 2018. https://www.epa.gov/pm-pollution/particulate-matter-pm-basics.
[19] Ibid.
[20] United States Environmental Protection Agency. "Basic Information about Carbon Monoxide (CO) Outdoor Air Pollution." Carbon Monoxide (CO) Pollution in Outdoor Air. Last modified September 8, 2016. https://www.epa.gov/co-pollution/basic-information-about-carbon-monoxide-co-outdoor-air-pollution.

Ozone is one of the components of smog, which can make air harmful to breathe when concentrations are elevated, especially for sensitive populations.[21] Nitrogen dioxide (NO_2) and other nitrogen oxides (NO_X) contribute to the formation of ozone, along with volatile organic compounds (VOC). Nitrogen dioxide can also cause respiratory issues, including acute and chronic effects, and it can contribute to acid rain and haze.[22] Because NO_X is more commonly measured and includes NO_2, NO_X is used as a proxy measurement for NO_2 in this report. This report also includes VOC emissions as an important ozone precursor.

Lead can cause a number of systemic negative effects in humans, plants, and animals, including the nervous system, reproductive and developmental systems, and the cardiovascular system,.[23] Diesel fuel, used for transporting the lime residuals, does not contain lead, and recent data showed lead emissions were less than 20 lbs/year for a local cement manufacturer[24] and <1 lb/year for a local lime manufacturer.[25] Therefore, this report assumes lead emissions for all three alternatives are negligibly small and focuses on emissions for the other pollutants listed above.

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[21] United States Environmental Protection Agency. "Ground-level Ozone Basics." Ground-level Ozone Pollution. Last modified October 31, 2018. https://www.epa.gov/ozone-pollution/basic-information-about-ozone.

[22] United States Environmental Protection Agency. "Basic Information about NO2." Nitrogen Dioxide (NO2) Pollution. Last modified September 8, 2016. https://www.epa.gov/no2-pollution/basic-information-about-no2.

[23] United States Environmental Protection Agency. "Basic Information about Lead Air Pollution." Lead Air Pollution. Last modified November 29, 2017. https://www.epa.gov/lead-air-pollution/basic-information-about-lead-air-pollution.

[24] United States Environmental Protection Agency. "Search Results - Facility ID 78610TXSLHLOOP4." Pollution Prevention. Last modified 2018. https://ofmpub.epa.gov/enviro/P2_EF_Query.p2_report?FacilityId=78610TXSLHLOOP4&ChemicalId=N420&ReportingYear=20 17&DocCtrlNum=.

[25] United States Environmental Protection Agency. "Form R - Austin White Lime Co." TRI. Last modified 2018. https://ofmpub.epa.gov/enviro/tri_formr_partone_v2.get_thisone?rpt_year=2017&dcn_num=1317215925239&ban_flag=Y.

Carbon dioxide (CO_2) is another major pollutant. In 2016, CO_2 represented 82% of the United States' greenhouse gas emissions.[26] This report also quantifies the impacts of each of the three alternatives on CO_2 emissions.

GENERAL ASSUMPTIONS AND CALCULATIONS

Tables 2.1 and 2.2 list assumptions used to calculate emissions for all three alternatives, based on the author's experiences in the water treatment industry.

Parameter	Quantity	Units
Water treatment flowrate	90,000	million gallons (MG)/year
Water treatment flowrate	247	million gallons/day (MGD)
Lime dosage	115	mg/L as CaO
Mass of dry residuals generated per mass of quicklime added	2.5	Dry lb/lb or dry ton/ton
Solids content of residuals (as sludge)	55	Percent (%) solids
Conversion factor	8.34	lb/MG per mg/L[28]

Table 2.1: Water Treatment Assumptions

[26] *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016*. Publication no. EPA 430-R-18-003. January 2018. https://www.epa.gov/sites/production/files/2018-01/documents/2018_complete_report.pdf. Page ES-8.

[28] Calculation: (1 mg/L) * (1 lb/453,592 mg) * (3.785 L/gal) * (1,000,000 gal/MG) = 8.34 lb/MG

Parameter	Quantity	Units
Vehicle type	18-wheel end-dump trucks	
Empty truck weight	31,000	lbs
Full truck weight	72,500	lbs
Load size	41,500	lbs
Fuel type	Diesel	

Table 2.2: Transportation Assumptions

Because any long-term lime residuals management alternative should be sufficient to meet current and future needs, 90,000 MG/year was selected based on Austin Water's projected 2070 water demand.[29] These assumptions are valid for lime softening water treatment plants in the Central Texas area using ferric sulfate as a coagulant and centrifuging their lime residuals to increase the solids content to 55%. The assumptions listed in Tables 2.1 and 2.2 are used to calculate the environmental and economic effects of the three alternatives. The total amount of lime used per day is calculated by multiplying the water treatment flowrate by the lime dose and the conversion factor (8.34). Multiplying the total amount of lime used per day by the solids production rate yields the production rate as dry solids. To calculate the sludge production rate, divide the dry solids residuals production rate by the solids content in the sludge.

$$\textit{Total Lime Use} = (\textit{Flow}) * (\textit{Lime Dose}) * (8.34) \qquad (\textit{Equation 3})$$

$$= (247\ \textit{MGD}) * (115\ \textit{mg/L}) * (8.34)$$

[29] City of Austin. "Water Forward - Austin's Integrated Water Resource Plan: January 31, 2017." Austin Water: Water Forward. Last modified July 3, 2017. Accessed December 3, 2018. http://austintexas.gov/sites/default/files/files/Water/WaterForward/Disaggregated_Demand_Model_Presentation_2_7.3.2017.pdf.

= 236,490 lbs/day or 118 tons/day

*Residuals Production = (Total Lime Use) * (Solids Production Rate) (Equation 4)*

*= (118 tons/day) * (2.5 dry lb/lb)*

= <u>296 tons/day as dry solids</u>

(296 tons/day) / (0.55% solids) = <u>537 tons/day as sludge</u> (Equation 5)

REGISTERED DISPOSAL SITE

As the lime residuals do not off-gas, the only emissions associated with using a registered disposal site are due to transportation. (Of course, preparing a registered disposal site might involve construction and generate additional emissions during the construction process; the amount of site work would vary depending on the disposal site. For the purposes of this report, it was assumed the site is ready to receive residuals, such as an old quarry, and no site work is necessary.) As illustrated in Figure 2.1, the EPA classifies heavy-duty vehicles by their weight.

Heavy-Duty Vehicle Classifications

(Gross Vehicle Weight Rating)

IIb:	8,501-10,000 lb (e.g., full-size pick-up trucks, very large passenger vans)
III:	10,001-14,000 lb (e.g., panel trucks, small enclosed delivery trucks)
IV:	14,001-16,000 lb (e.g., city delivery trucks, rental trucks)
V:	16,001-19,500 lb (e.g., bucket utility trucks, large walk-in delivery trucks)
VI:	19,501-26,000 lb (e.g., rack trucks, single axle vans)
VII:	26,001-33,000 lb (e.g., tow truck, garbage collection trucks)
VIIIa:	33,001-60,000 lb (e.g., long-haul semi-tractor trailer rigs)
VIIIb:	> 60,000 lb (e.g., double long-haul semi-tractor trailer rigs)

Figure 2.1: EPA Vehicle Classification[30]

Using Figure 2.1, an empty truck would be classified as VII, and a full truck would be classified as VIIIb. The EPA also provides average emissions rates based on the vehicle classification and fuel type as shown in Table 2.3.

[30] United States Environmental Protection Agency Office of Transportation and Air Quality. *Average In-Use Emissions from Heavy-Duty Trucks.* Report no. EPA420-F-08-027. October 2008. https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100EVY6.TXT. Page 4.

Pollutant	Fuel	IIb	III	IV	V	VI	VII	VIIIa	VIIIb
VOC	gas	1.353	1.667	4.234	2.632	2.477	2.857	3.628	(1)
	diesel	0.189	0.201	0.262	0.274	0.365	0.453	0.455	0.545
	gas	1.400	1.713	4.319	2.693	2.535	2.920	3.704	(1)
	diesel	0.194	0.204	0.266	0.278	0.370	0.459	0.461	0.552
CO	gas	11.220	15.810	33.860	19.580	18.130	23.130	28.560	(1)
	diesel	0.839	0.908	1.163	1.189	1.367	1.719	2.395	3.109
NOx	gas	2.734	2.920	4.133	3.735	3.650	4.199	4.892	(1)
	diesel	3.088	3.298	4.352	4.548	5.990	7.471	9.191	10.990
PM2.5	gas	0.043	0.045	0.058	0.046	0.045	0.046	0.049	(1)
	diesel	0.091	0.073	0.089	0.079	0.172	0.177	0.215	0.238
PM10	gas	0.049	0.051	0.074	0.055	0.054	0.056	0.061	(1)
	diesel	0.099	0.079	0.096	0.085	0.186	0.192	0.233	0.259

(1) There are no gasoline-fueled heavy trucks in this weight category.

Table 2.3: Average Heavy-Duty Truck Emission Rates by GVW Class (grams/mile)[32]

A 2017 study found the average vehicle emissions rate of a 2013/2014 diesel truck (total weight of 68,000 lbs) was 1,667 g CO_2/mile on a regional highway route[33], which approximate the emissions of a lime residuals truck when carrying a full load. "The Regional Highway Route included trips with less than 80% of operation above 40 mi/hr, where lower-speed operation resulted from urban congestion and more frequent highway interchanges (trip average and SD ¼ 34.0 ± 6.45 mi/hr),"[34] which was assumed to be consistent with lime residuals trucks' regular hauling speeds. A 2015 National Highway Traffic Safety Administration (NHTSA) report found a tractor-trailer weighing 33,960 lbs had a fuel economy of 9.26 miles/gallon (mpg) with no payload, 8.12 mpg with 23,020 lbs

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32 Ibid. Page 5.

33 Quiros, David C., Jeremy Smith, Arvind Thiruvengadam, Tao Huai, and Shaohua Hu. "Greenhouse gas emissions from heavy-duty natural gas, hybrid, and conventional diesel on-road trucks during freight transport." *Atmospheric Environment* 168 (November 2017): 36-45. https://doi.org/10.1016/j.atmosenv.2017.08.066. Page 40.

34 Ibid. Page 39.

of payload, and 7.22 mpg with 46,040 lbs of payload.[35] Through linear interpolation, this report assumes a truck with the same base weight carrying a payload of 41,500 lbs (the size of a lime residuals payload) would have a fuel efficiency of 7.71 mpg. As the fuel efficiency of an empty truck is 20% better than the fuel efficiency of a truck carrying 41,500 lbs, it was assumed the CO_2 emissions would be 20% less (or 80% of the total) when the truck was empty.

$$80\% * 1{,}667 \text{ g } CO_2/\text{mile} = 1{,}334 \text{ g } CO_2/\text{mile} \qquad \text{(Equation 6)}$$

Diesel used to contain up to 5,000 parts per million (ppm) sulfur content.[36] To address high sulfur emissions, the EPA mandated all highway diesel fuel vehicles must use Ultra-Low Sulfur Diesel (ULSD), which contains a maximum of 15 ppm sulfur content, by 2010.[37] While updated data on sulfur emissions due to heavy vehicles could not be identified, it is assumed that sulfur emissions from diesel trucks are considerably less than NO_X, CO, and PM emissions. Due to the lack of sulfur dioxide emissions data for residuals transportation, sulfur dioxide is not included in this analysis.

Lime residuals transportation emissions will depend on the number of truck trips made per day to haul the lime residuals to the registered disposal site. Table 2.4 calculates the number of truck trips/day necessary to haul the lime residuals from the water treatment plant to the registered disposal site using the assumptions listed in Tables 2.1 and 2.2.

[35] U.S. Department of Transportation National Highway Traffic Safety Administration. *Commercial Medium- and Heavy-Duty Truck Fuel Efficiency Technology Study - Report #1*. By Thomas E. Reinhart. Report no. DOT HS 812 146. October 2015. https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/812146-commercialmdhd-truckfuelefficiencytechstudy-v2.pdf. Page 65.
[36] United States Environmental Protection Agency. "Diesel Fuel Standards and Rulemakings." Diesel Fuel Standards. Last modified June 7, 2017. https://www.epa.gov/diesel-fuel-standards/diesel-fuel-standards-and-rulemakings.
[37] Ibid.

Parameter	Quantity	Units
Lime Residuals Produced (55% solids)	537	tons/day
Truck Capacity	41,500	lbs
Truck Capacity	20.75	tons
Average Truck Trips	25.9	trucks/day

Table 2.4: Number of Truck Trips Required per Day

Because some utilities will have the ability to select a registered disposal site closer to their water treatment plant(s) than others, Tables 2.5 lists emissions for varying distances between the water treatment plant(s) and the registered disposal site. Transportation emissions were calculated assuming 25.9 truck trips are required per day per Table 2.4 and using the emissions rates listed above.

Pollutant	**Distance from WTP to Registered Disposal Site (miles)**			
	0-5 (2.5)	**5-10 (7.5)**	**10-15 (12.5)**	**15-20 (17.5)**
$PM_{2.5}$	22	65	108	151
PM_{10}	24	71	118	165
CO	252	755	1,258	1,761
NO_X	962	2,886	4,810	6,734
VOC	52	156	260	364
CO_2	156,357	469,071	781,785	1,094,499

Table 2.5: Transportation Emissions for Registered Disposal Site (lb/year)

Lime residuals are classified as a solid waste per Title 40 of the Code of Federal Regulations (40 CFR) Part 257.[38] Use, transportation, and disposal of lime residuals, which the TCEQ terms water treatment sludge, are regulated under Texas Administrative Code (30 TAC) Chapter 312 Subchapter F.[39] The rules in Subchapter F are relatively brief, with only nine clauses in the entire subchapter.[40] Utilities are expected to do their due diligence in lime residuals disposal by complying with the items listed in Table 2.6.

Comply with Title 30 of the Texas Administrative Code (30 TAC) Chapter 312
Comply with Title 40 of the Code of Federal Regulations (40 CFR) Part 257
Prevent restriction of storm water flow
Prevent runoff and protect of surface water quality
Protect underground drinking water sources beyond the site boundary
Limit land application used to produce food chain crops
Restrict of public access

Table 2.6: Regulatory Requirements for Registered Disposal Sites[41]

Lime residuals samples are collected annually and analyzed by an accredited lab to verify the residuals' concentrations of heavy metals, harmful chemicals, and other contaminants of concern are acceptably low. As the lime residuals are inert, non-hazardous,

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38 40 C.F.R. § 257.2 (2016) (Legal Information Institute).
39 30 Tex. Admin. Code § 312 (2005).
40 Ibid.
41 Linendoll, Chris. Unpublished Letter to Charles R. Maddox, May 21, 2015. Re: City of Austin - Austin Water Utility - Approval of Registration Number: 730010. Texas Commission on Environmental Quality, Austin, TX.

and primarily composed of calcium carbonate, a liner is not required to dispose of the lime residuals on a registered disposal site. The largest environmental concern associated with a registered disposal site is some sort of spill allowing the lime residuals to travel offsite. The lime residuals have a basic pH[42], and sufficiently large quantities of lime residuals could harm aquatic life. Water and soil pollution are not major risks so long as the registered disposal site has proper barriers in place to prevent residuals from leaving the site via stormwater runoff, so water and soil pollution risks are not included in this report.

CEMENT MANUFACTURING

To use lime residuals in cement manufacturing, it is assumed that a utility would first transport the lime residuals to a registered disposal site as 55% solids, allow the lime residuals to air-dry while open to the atmosphere to approximately 77% solids, and then haul the air-dried residuals to a cement manufacturing plant. This analysis assumes the trucks used to haul the air-dried lime residuals will be the same size and carry the same size payload as in the previous section. To calculate the environmental impact of reusing lime residuals in cement manufacturing, the types of emissions listed in Table 2.7 must be considered.

[42] Varying from 9.3-11.0 based on unpublished data collected from 2010-2016.

Emissions due to transportation to/from the registered disposal site (varying distances assumed from 0-20 miles per Table 2.5)
Emissions due to transportation to/from the cement manufacturer (assumed to be 20 miles)
Reduction in emissions due to replacement of lime residuals in portland cement (assumed to be 1:1 replacement)[43]

Table 2.7: Types of Emissions for Cement Manufacturing

For cement manufacturers to find it economically advantageous to use lime residuals in their process, the lime residuals will need to be nearby and available at an extremely low or no cost. For the purposes of this report, it is assumed that an interested cement manufacturer is 20 miles away from the registered disposal site based on the frequency and distribution of cement manufacturers in the Central Texas area.[44] Transportation emissions are presented in Table 2.8 using the same distance ranges between the WTP(s) and the registered disposal site with an additional 20 miles of transportation included for transportation of the lime residuals from the registered disposal site to the cement manufacturer.

[43] 1:1 replacement assumes lime residuals will be substituted into portland limestone cement at the end of the cement manufacturing process as limestone is currently substituted.
[44] Lute, Racheal, Thano Drimalas, and Kevin Folliard. "Beneficial Use of Lime Residuals in Industrial and Infrastructure Applications: A Feasibility Study." Unpublished manuscript, The University of Texas at Austin, Austin, TX, June 30, 2017. Page 46.

Pollutant	Total Distance (WTP – Registered Disposal Site – Cement Manufacturer) (miles)			
	20-25 (22.5)	**25-30 (27.5)**	**30-35 (32.5)**	**35-40 (37.5)**
$PM_{2.5}$	195	238	281	324
PM_{10}	212	259	306	353
CO	2,264	2,767	3,271	3,774
NO_X	8,658	10,582	12,506	14,430
VOC	468	572	676	780
CO_2	1,407,213	1,719,928	2,032,642	2,345,356

Table 2.8: Transportation Emissions for Cement Manufacturing (lb/year)

Emissions from cement manufacturers can vary drastically depending on the manufacturer's permitted emissions limits, the type of cement and equipment used at the cement plant, voluntary or mandatory implementation of emissions reducing technology, and other factors. With that in mind, the best estimate of the reduction in cement manufacturing emissions due to replacement of portland cement with lime residuals in Texas would be from a local Texas manufacturer. The Capital Area Council of Governments' (CAPCOG) Air Quality Program prepared a Point Source Emissions Inventory Refinement report in 2015, which includes emissions data from a local cement manufacturer and is the basis for the following cement manufacturing emissions analysis.[45]

[45] Capital Area Council of Governments Air Quality Program. Point Source Emissions Inventory Report. Austin, TX, 2015. http://www.capcog.org/documents/airquality/reports/2015/Point_Source_Emissions_Inventory_Refinement.08-31-15.pdf.

Cement manufacturers emit roughly 1 ton of CO_2 per ton of cement manufactured.[46] Roughly 50% of the CO_2 is generated from the calcination process, 40% is from burning fuel to heat the kiln (thermal), and 10% is from other/indirect causes, such as blasting, transportation, and other on-site processes.[47] For the purposes of this report, substituting lime residuals for portland cement is assumed to reduce emissions from the calcination and thermal processes (90%) but not from the remaining 10% of CO_2 emissions.

Table 2.9 shows the local cement manufacturer's average annual emissions and the projected reduction in emissions associated with substituting lime residuals at the end of the process, creating a cement with 5% lime residuals. It is worth noting that the results below represent a reduction due to a 5% replacement at just the one local facility that participated in the CAPCOG study, equivalent to reusing 169 tons/day of lime residuals. This report assumes an available supply of 296 tons/day of lime residuals.

[46] United Nations Environment Programme. "Greening Cement Production has a Big Role to Play in Reducing Greenhouse Gas Emissions." Environmental Science Alert. Last modified October 2010. https://na.unep.net/geas/science/alert_2010_10.php.
[47] Rubenstein, Madeleine. "Emissions from the Cement Industry." State of the Planet - Climate. Last modified May 9, 2012. https://blogs.ei.columbia.edu/2012/05/09/emissions-from-the-cement-industry/.

Pollutant	Average Emissions	Emissions Reduction due to Lime Residuals Replacement (5%)	Units[48]
$PM_{2.5}$	77	3.9	tons/yr
PM_{10}	265	13	tons/yr
CO	3,575	179	tons/yr
NO_X	2,364	118	tons/yr
VOC	183	9.1	tons/yr
CO_2*	1,111,018	55,551	tons/yr

*CO_2 only includes calcination and thermal CO_2 production, which is 90% of total CO_2 emissions

Table 2.9: Lime Residuals Reduction in Emissions at One Local Cement Manufacturer

Typically, many lime manufacturers cluster in a single geographic area to maximize use of the area's natural limestone, so it is reasonable to assume the local cement manufacturing market will have the ability to beneficially reuse the full 296 tons/day of dry solids generated by the water treatment process examined in this study (see Tables 2.1 and 2.2). Table 2.10 summarizes the estimated net reduction in emissions resulting from reusing 296 tons/day of lime residuals in cement manufacturing, including emissions due to transportation from the water treatment plant to the registered disposal site and from the registered disposal site to the cement plant.

48 Unless stated otherwise, "tons" refers to U.S. tons or 2,000 lbs.

Pollutant	Total Distance (WTP - Registered Disposal Site – Cement Manufacturer) (miles)			
	20-25 (22.5)	**25-30 (27.5)**	**30-35 (32.5)**	**35-40 (37.5)**
$PM_{2.5}$	6.7	6.6	6.6	6.6
PM_{10}	23	23	23	23
CO	311	311	311	311
NO_X	202	201	200	199
VOC	16	16	16	16
CO_2	96,405	96,249	96,093	95,936

Table 2.10: Annual Net Emissions Reduction at Full Market Utilization (tons)

Even with up to 40 miles of transportation emissions (from the water treatment plant to the registered disposal site and from the registered disposal site to the cement manufacturer), beneficially reusing lime residuals in cement manufacturing still has significant environmental benefits with respect to emissions reduction.

RECALCINATION

To minimize the amount of heat necessary to dry the lime residuals, the lime residuals should be as dewatered as possible for recalcination. Therefore, this report assumes the recalcination would occur at the registered disposal site, allowing the residuals to air-dry to approximately 77% solids. Emissions generated during construction of the recalcination facility will be highly site-specific depending on the amount of construction required and are anticipated to be significantly less than the long-term emissions from recalcination over time, so emissions from construction of the recalcination facility are ignored. Because the recalcination process and the lime manufacturing process are very similar (converting calcium carbonate to calcium oxide) and occur at similar temperatures (898 degrees C for lime manufacturing[49] and 1,010 degrees C for recalcination[50]), lime manufacturing emissions are assumed to provide a reasonable estimate of recalcination emissions. As was briefly discussed in Chapter 1, this report assumes the CO_2 generated during recalcination is not captured and therefore contributes to emissions.

The 2015 CAPCOG Point Source Emissions Inventory Refinement report also provided emissions data from a local lime manufacturer.[51] Particulate matter emissions were only reported as a single number; this report assumes that value includes combined $PM_{2.5}$ and PM_{10} emissions. As no CO_2 emissions data were provided, it was assumed that producing 1 lb of lime via recalcination generates 0.75 lbs of CO_2 per the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.[52] Because the lime manufacturer did not provide any production information, emissions due to lime residuals recalcination were interpolated using the comparative energy inputs between the two facilities assuming a linear correlation between energy inputted and emissions outputted. The results of this analysis are shown in Table 2.11.

[49] Crump, Eric L. *Lime Production: Industry Profile*. United States Environmental Protection Agency Office of Air Quality Planning and Standards: Innovative Strategies and Economics Group, Research Triangle Park, NC, 2000. https://www3.epa.gov/ttnecas1/regdata/IPs/Lime%20Manufacturing_IP.pdf. Page 2-4.

[50] Michel, Hani Emil. "Technical Memorandum No. 10: Residuals Management." Unpublished manuscript, Carollo Engineers, Austin, TX, December 2008. Page 10-8.

[51] Capital Area Council of Governments Air Quality Program. Point Source Emissions Inventory Report. Austin, TX, 2015. http://www.capcog.org/documents/airquality/reports/2015/Point_Source_Emissions_Inventory_Refinement.08-31-15.pdf.

[52] Harnisch, Jochen, and William Kojo Agyeman-Bonsu. *Industrial Processes and Product Use*. Edited by Jamidu H.Y. Katima and Audun Rosland. Vol. 3 of *IPCC Guidelines for National Greenhouse Gas Inventories.* Intergovernmental Panel on Climate Change, 2006. https://www.ipcc.ch/meetings/session25/doc4a4b/vol3.pdf. Page 2.22.

Pollutant	Annual Emissions (tons)
PM	9.1
CO	34
NO_X	175
VOC	1.3
CO_2	22,830

Table 2.11: Estimated Emissions due to Lime Residuals (77% Solids) Recalcination

The emissions due to transportation of the lime residuals to the registered disposal site are the same as in the first alternative as per Table 2.12.

Pollutant	Distance from WTP to Registered Disposal Site (miles)			
	0-5 (2.5)	5-10 (7.5)	10-15 (12.5)	15-20 (17.5)
$PM_{2.5}$	22	65	108	151
PM_{10}	24	71	118	165
CO	252	755	1,258	1,761
NO_X	962	2,886	4,810	6,734
VOC	52	156	260	364
CO_2	156,357	469,071	781,785	1,094,499

Table 2.12: Annual Transportation Emissions to Registered Disposal Site (lbs)

Combining the emissions due to recalcination and the emissions due to transportation yields Table 2.13.

Pollutant	Distance from WTP to Registered Disposal Site (miles)			
	0-5 (2.5)	5-10 (7.5)	10-15 (12.5)	15-20 (17.5)
PM	9.2	9.2	9.2	9.3
CO	34	34	34	35
NO_X	175	176	177	178
VOC	1.3	1.4	1.4	1.5
CO_2	22,908	23,064	23,221	23,377

Table 2.13: Annual Emissions from Recalcination (tons)

Because calcium is the major component of hardness in Central Texas, lime residuals contain significantly more calcium than what is added as lime during the water treatment process. Therefore, recalcination can provide more lime than a utility might need. As was mentioned in Chapter 1, a utility should not replace more than 80% of its lime dosage with recalcinated residuals to minimize the risk of concentrating undesirable constituents in the drinking water.[53] Recalcining 296 dry tons of sludge/day would produce 166 tons/day of recalcinated lime. As the amount of lime needed by the utility was calculated to be 118 tons/day (see Chapter 2) and only 80% of the lime would be substituted with recalcinated lime, the utility would only have a need for 95 tons/day of recalcinated lime. This leaves 71 tons/day of recalcinated lime available to sell to interested parties.

It is worth noting that, if all of the recalcinated lime was used to replace existing lime uses within and outside the utility, the increased emissions due to recalcination would effectively be offset by the emissions reduction due to the reduction of lime manufacturing

[53] Michel, Hani Emil. "Technical Memorandum No. 10: Residuals Management." Unpublished manuscript, Carollo Engineers, Austin, TX, December 2008. Page 10-8.

in the area. Shifting the emissions burden from the private sector to a municipal utility can create the perception of not being environmentally friendly and might therefore make recalcination undesirable for a utility, even if the social impact of the change is negligible.

COMPARISON

Table 2.14 summarizes the emissions impact of each of the three alternatives, assuming the furthest distance (15-20 miles) between the WTP and the registered disposal site as the worst-case scenario for all three alternatives:

Pollutant	**Registered Disposal Site**	**Cement Manufacturing**	**Recalcination**
$PM_{2.5}$	0.08	(6.6)	9.3
PM_{10}	0.08	(23)	
CO	0.88	(311)	35
NO_X	3.4	(199)	178
VOC	0.18	(16)	1.5
CO_2	547	(95,936)	23,377

Table 2.14: Annual Net Emissions Associated with Lime Residuals (tons)

Compared to the significant emissions (or emissions reduction) from cement manufacturing and recalcination, the transportation emissions built into each alternative are minimal. Cement manufacturing produces more emissions than recalcination/lime manufacturing, so it makes sense that the emissions reduction achieved by using the lime residuals in cement manufacturing is more than the amount of emissions produced by using the lime residuals for recalcination.

Recalcination causes the highest level of emissions, but on a wider scale those emissions will likely be offset by a reduction in emissions due to a reduction in lime manufacturing. If the recalcination site and the WTP(s) were in close proximity, it would be economically viable to capture, transport, and reuse the CO_2 generated as a product of the recalcination reaction, further reducing emissions. However, this report assumes the WTP(s) and the registered disposal site with the rotary kiln for recalcination are 15-20 miles away from each other, so transporting the CO_2 is prohibitively expensive.

Chapter 3: Economic Evaluation

Utilities decide how to manage lime residuals based economic and environmental factors, so any selected alternative must be cost effective. This chapter compares the costs associated with each alternative, including capital (startup) and operations and maintenance (O&M) costs.

CAPITAL COSTS

Capital costs for each facility were identified as shown in Table 3.1.

Expense	**Registered Disposal Site**	**Cement Manufacturing**	**Recalcination**
Land	X	X	X
Kiln			X

Table 3.1: Capital Costs for Each Alternative

All three sites include the base cost of a registered disposal site for storage and drying of lime residuals. For each alternative, the cost of land will be the same and is assumed to be $2M in 2018 dollars based on a recent unpublished evaluation of a 27-acre site in Austin. The only difference in the capital costs is the kiln. Estimated lime residuals production is anticipated to be 296 tons of dry solids/day, equivalent to 537 tons of 55% solids/day or 385 tons of 77% solids/day. Kiln operations favor feeding the kiln 77% solids lime residuals to save energy by minimizing the amount of water the kiln has to burn off. However, it is more conservative to size the kiln assuming 537 tons/day of 55% solids in case the drier residuals become inaccessible or lime residuals production exceeds estimations. With that in mind, a 600 ton/day kiln is recommended.

One estimate for the cost of a 600 ton/day kiln is $20.25M in 2008 dollars.[54] From 2008 until 2018, there has been a 17.11% increase in prices due to inflation.[55] Capital costs for a 600 ton/day kiln in 2018 dollars are shown in Table 3.2.

Item	**Cost**
Base Cost - Kiln (2018 dollars)	$23,714,775
Contractor Overhead/Profit (15%)	$3,557,216
Contingency (15%)	$3,557,216
Total Construction Cost	$30,829,208
Engineering (20% of Total Construction Cost)	$6,165,842
Total Project Cost	**$36,995,049**

Table 3.2: Kiln Capital Costs (2018 USD)

Total capital costs for each alternative are presented in Table 3.3

Capital Costs	**Registered Disposal Site**	**Cement Manufacturing**	**Recalcination**
Land	$2,000,000	$2,000,000	$2,000,000
Kiln	$0	$0	$ 36,995,049
Total	**$2,000,000**	**$2,000,000**	**$38,995,049**

Table 3.3: Total Capital Costs (2018 USD)

[54] Michel, Hani Emil. "Technical Memorandum No. 10: Residuals Management." Unpublished manuscript, Carollo Engineers, Austin, TX, December 2008. Page 10-16.
[55] Official Data Foundation. "U.S. Inflation Rate, $20,250,000 in 2008 to 2018." CPI Inflation Calculator. Last modified 2018. http://www.in2013dollars.com/2008-dollars-in-2018?amount=20250000.

As expected, recalcination has significantly higher capital costs than the other alternatives because of the high price of the kiln.

OPERATIONS AND MAINTENANCE (O&M) COSTS

A variety of operations and maintenance (O&M) costs were considered for this analysis to capture the long-term costs associated with each alternative.

Staffing

Staffing costs per employee were calculated for each alternative based on average wages and benefits in Austin[56] and are listed in Table 3.4.

Expense	Truck Driver	O&M Assistant
Median Base Salary	$46,241	$54,974
Benefits[57]	$20,511	$22,766
Total Annual Cost Per Employee	**$66,752**	**$77,740**

Table 3.4: Annual Cost per Employee (2018 USD)

Table 3.5 lists staffing needs for each alternative. Assuming hauling one load takes two hours, nine employees are needed to transport residuals from the WTPs to the registered disposal site. Based on the ratio of 77% solids to 55% solids and assuming the same load time, an additional seven employees are needed to transport residuals from the

[56] "Government Salaries Explorer." The Texas Tribune. Last modified July 25, 2018. https://salaries.texastribune.org.
[57] Benefits include employer retirement contribution, medical and dental insurance, basic life insurance, short term disability, and employer Social Security and Medicare contributions based on the author's unpublished experience

registered disposal site to the recalcination facility. To ensure at least two employees are on site at all times, eight employees are needed to operate and maintain the kiln (assuming an on- and off-rotation day shift and night shift).

Alternative	Truck Driver	O&M Assistant	Total
Registered Disposal Site	9	0	**9**
Cement Manufacturing	16	0	**16**
Recalcination	9	8	**17**

Table 3.5: Staffing Needs

Table 3.6 calculates staffing costs for each alternative using the annual cost per employee and staffing needs calculated above.

Alternative	Truck Driver	O&M Assistant	Total
Registered Disposal Site	$600,768	$-	**$600,768**
Cement Manufacturing	$1,068,032	$-	**$1,068,032**
Recalcination	$600,768	$621,917	**$1,222,685**

Table 3.6: Staffing Costs (2018 USD)

Staffing costs are highest for recalcination, followed by cement manufacturing. The registered disposal site alternative has the lowest staffing costs as it is the least labor-intensive alternative.

Transportation

Table 3.7 lists transportation costs for each alternative, assuming each truckload could haul 41,500 lbs and each load takes two hours total (including filling, transportation each way, and offloading).

Alternative	Loads/Day	Hrs/Load	Truck Cost/Hr[58]	Cost/Day
Registered Disposal Site	25.90	2	$ 7.227	**$ 374.40**
Cement Manufacturing	44.48	2	$ 7.227	**$ 642.87**
Recalcination	25.90	2	$ 7.227	**$ 374.40**

Table 3.7: Transportation Costs (2018 USD)

The total transportation cost is most expensive for cement manufacturing as it requires additional transportation to the cement manufacturer. Transportation costs for the registered disposal site and for recalcination are the same.

Fuel for Recalcination

This analysis assumes the recalcination kiln will be fueled by natural gas, particularly given current low natural gas prices. A utility in Ohio practicing recalcination to reuse its lime residuals at 70% solids uses 7.9 MBTU[59] per ton of lime residuals.[60] This report assumes the energy needed for recalcination will be linear with respect to the solids content of the lime residuals. Lime residuals with a higher solids content have less water that needs to be evaporated and will therefore require less energy to recalcinate than lime residuals with a lower solids content. As the air-dried lime residuals analyzed in this report

[58] Unpublished information based on the author’s experience, including fuel and vehicle wear/tear
[59] Million BTUs, a standard unit of measurement for energy provided by natural gas
[60] Michel, Hani Emil. "Technical Memorandum No. 10: Residuals Management." Unpublished manuscript, Carollo Engineers, Austin, TX, December 2008. Page 10-13.

are 77% solids, it is assumed that recalcination will require 7.1 MBTU/ton of lime residuals. 296 dry tons/day is equivalent to 537 tons/day as 55% solids as was shown in Equation 5, which is equivalent to 385 tons/day as 77% solids. As indicated in Table 3.8, fuel will cost nearly $3M per year to recalcinate 385 tons/day at a natural gas price of $3.19/1000ft^3.

Parameter	**Value**	**Units**
Heat Needed at 77% solids	7.1	MBTU/ton
Recalcinated residuals	385	tons/day
Heat Needed at 77% Solids	2,750	MBTU/day
Cost of Natural Gas[61]	$3.19	per 1000 ft^3
Heat Provided by Natural Gas[62]	1,100	BTU/ft^3
Fuel Needed	2,500,109	ft3/day
Fuel Needed	2,500	1000 ft^3/day
Cost	$7,975.35	per day
Total Cost	**$2,911,002**	**per year**

Table 3.8: Fuel Costs (2018 USD)

[61] United States Energy Information Administration. Natural Gas Prices: Texas. Last modified November 30, 2018. https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_STX_m.htm.
[62] Cement Equipment. "Every Thing you need to know about Cement Kiln Fuels." Infinity for Cement Equipment. http://www.cementequipment.org/home/firing-systems/every-thing-need-know-cement-kiln-fuels/.

Chemical Usage Savings

One major financial incentive to recalcinate lime residuals is to reduce the amount of money spent on lime. Table 3.9 indicates how much lime will be generated in the recalcination process and quantifies how much recalcinated lime can be used in-house or sold as excess lime.

Parameter	Value	Units
Lime Addition (CaO)	118	ton/day
Recalcinated Lime Generated (CaO)	166	ton/day
Recalcinated Lime Used In-House (CaO)	95	ton/day
Excess Lime Generated	71	ton/day

Table 3.9: Recalcinated Lime Production

Table 3.10 reports the savings due to recalcination assuming the utility is charged $127/ton of lime and any excess lime generated is sold at 50% the current lime cost.

Parameter	Value	Units
Savings from Reduced Lime	$12,014	per day
Excess Revenue Generated	$4,511	per day
Total Savings	**$16,524**	**per day**
	$6,031,417	**per year**

Table 3.10: Annual Savings from Recalcinated Lime Residuals (2018 USD)

While there are significant additional fuel costs associated with recalcination, the chemical cost savings (just over $6M/year) are greater than the fuel costs (almost $3M/year).

Total O&M Costs

Table 3.11 lists the total annual O&M costs for the three alternatives.

Alternative	Labor	Transportation	Fuel	Lime	Total
Registered Disposal Site	$600,768	$136,654	$0	$0	**$737,422**
Cement Manufacturing	$1,068,032	$234,647	$0	$0	**$1,302,678**
Recalcination	$1,222,685	$136,654	$2,911,002	$(6,031,417)	**$(1,761,076)**

Table 3.11: Annual O&M Costs (2018 USD)

Recalcination is the least expensive with a net savings of $1.76M/year. The registered disposal site is second-most affordable with a total cost of $0.74M/year. Cement manufacturing is the most expensive alternative with a total cost of $1.3M/year.

SOCIAL COST OF POLLUTION

Emitting pollutants into the environment causes a number of problems. In addition to the negative health effects on humans and the environment, pollution can also decrease the value of natural resources. Natural resources provide food, materials, energy, and recreation for humans; perform ecological functions; and are inherently valued for beauty and biodiversity.[63] Depleting, ruining, or destroying natural resources can have economic and non-economic impacts. For example, climate change could cause negative effects on communities across the globe, including increased temperature-related mortality and morbidity, changes in crop growth, flooding, drought, increased heating and cooling costs, changes in water availability, necessity of human migration, and ecosystem impacts.[64]

The true value of resources lost and costs of environmental impacts are difficult to measure, making the cost of pollution difficult to quantify. A number of methods are available to estimate the economic value of natural resources, including market prices; simulated markets; stated preference (surveys); travel costs to recreational sites such as national parks; comparing property values for properties that do and do not have a specified resource, such as noise pollution, flooding, views, and recreation sites; and wage differentials for higher risk jobs.[65] Table 3.12 lists one procedure used to quantify the "social cost" of pollution.

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63 Olmstead, Shelia. "Topic 2. Estimating the benefits of (demand for) environmental and resource amenities." Lecture, Environmental and Resource Economics and Policy (PA 393L), The University of Texas at Austin, Austin, TX, January 29, 2018.
64 Olmstead, Sheila. "Topic 6. Climate Change." Lecture, Environmental and Resource Economics and Policy (PA 393L), The University of Texas at Austin, Austin, TX, March 19, 2018.
65 Olmstead, Shelia. "Topic 2. Estimating the benefits of (demand for) environmental and resource amenities." Lecture, Environmental and Resource Economics and Policy (PA 393L), The University of Texas at Austin, Austin, TX, January 29, 2018.

Step	Task
1	Project future greenhouse emissions.
2	Use projected emissions data to characterize physical climate change (temperature/precipitation changes, sea-level rise, etc.).
3	Estimate physical impacts of climate changes on humans and the environment.
4	Monetize the physical impacts.
5	Repeat Steps 1-4 with one additional ton of greenhouse gas emissions in the same year and calculate the change in cost.

Table 3.12: Procedure to Estimate Social Cost of Pollution[66]

Conceptually, the social cost of emissions is the cost of one additional ton of the pollutant of interest in a given year. Calculating the social cost of emissions is extremely complicated. Some complexities include:

- How large of a scale should be considered when looking at physical impacts? (Global? National? State? Local?)
- How should the effects of catastrophic events (e.g., storms, tsunamis, earthquakes) be estimated?
- What discount (inflation) rates should be used?

With these factors in mind, estimates of the social cost of pollution can vary significantly. The EPA estimates one metric ton (2,205 lbs) of carbon dioxide emissions in 2020 will have a social cost of $42 (2007 USD, 3% discount rate).[67]

[66] Olmstead, Sheila. "Topic 6. Climate Change." Lecture, Environmental and Resource Economics and Policy (PA 393L), The University of Texas at Austin, Austin, TX, March 19, 2018.
[67] United States Environmental Protection Agency. "The Social Cost of Carbon." Climate Change. Last modified January 9, 2017. https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html.

Table 3.13 lists the social costs of each alternative based the EPA's estimate of the social cost of carbon dioxide.

Alternative	Emissions (tons/year)	Cost (2018 USD/year)
Registered Site	547	$25,384
Cement Manufacturing	(95,936)	$(4,450,047)
Recalcination	23,377	$ 1,084,348

Table 3.13: Annual Social Cost of Carbon Dioxide (2018 USD)

Incorporating the social cost of carbon dioxide significantly changes the O&M costs for each alternative as shown in Table 3.14. Because of the emissions offset, cement manufacturing now also offers offering a cost savings. Recalcination is less desirable due to the social cost of emissions. However, social costs of pollution are not incurred directly by the utility and are offset by the reduced generation of lime elsewhere. Additionally, the social costs or savings included in this analysis only include the social costs of carbon dioxide. There are large social costs associated with other pollutants as well, though social costs for the other pollutants evaluated in this report have not been quantified at this time.

Alternative	O&M Costs Including Social Costs of CO_2
Registered Disposal Site	$762,807
Cement Manufacturing	$(3,147,369)
Recalcination	$(676,727)

Table 3.14: Total Annual O&M and Social Costs (2018 USD)

NET PRESENT VALUE (NPV) ANALYSIS

The net present value (NPV) of each alternative is shown in Table 3.15 assuming a 2.5% discount rate and a 50-year lifecycle. While recalcination provides the most long-term savings (roughly \$50M) when social costs are not included, the social costs of the CO_2 emissions associated with recalcination decrease the net present value to \$19M savings. If a utility chooses not to recalcinate its residuals, these emissions would likely be produced regardless by a local lime manufacturer to supply the utility with lime, but transferring the emissions production from the private industry to the utility might not be acceptable to some utilities. Beneficially reusing the lime residuals in cement manufacturing provides the most benefit when incorporating the social cost of carbon dioxide emissions (\$89M savings), but without considering social costs it is the most expensive alternative (almost \$37M). The registered disposal site has the least impact on emissions, so the cost of the registered disposal site is relatively similar with or without the social cost of CO_2 emissions included (\$21M without social costs and \$22M with social costs).

Net Present Value	**Registered Disposal Site**	**Cement Manufacturer**	**Recalcination**
No Social Costs	\$20,914,997	\$36,946,960	\$(49,948,174)
With Social Costs	\$21,634,958	\$(89,266,668)	\$(19,193,547)

Table 3.15: Net Present Value (2018 USD)

Chapter 4: Non-Economic Factors

The intent of this chapter is to provide an overview of the non-economic factors utilities must consider when selecting a lime residuals management strategy. A utility should consider the full impacts of any lime residuals disposal alternative before making a decision on what would be best for that utility and its customers, including public perception, managerial impacts, regulatory requirements, and the utility's values and organizational structure.

PUBLIC PERCEPTION

Utilities provide a public service and often are the subjects of public scrutiny. Table 4.1 lists some potential public perception issues associated with each of the three alternatives.

Public Perception	Registered Disposal Site	Cement Manufacturing	Recalcination
Longevity	Short-term	Long-term	Long-term
Appearance	Eyesore	Eyesore	Eyesore
Dust/Noise	Minimal	Minimal	Significant
Beneficial Use	Park	Reduces emissions	Reduces chemical costs
Environmental	Some emissions	Decreases emissions	Shifts emissions to utility
Economics	Inexpensive	Expensive	Cost Savings

Table 4.1: Public Perception Scorecard

Each disposal alternative includes positive and negative perceptions. For example, while a registered disposal site is inexpensive and has a minimal impact, customers might see a registered disposal site as a "band-aid" solution that does not truly solve the problem. Recalcination might be construed as harming the environment, even though the emissions due to recalcination would otherwise be emitted by a lime manufacturer. Beneficially reusing the lime residuals in cement manufacturing might give the appearance of favoring the cement manufacturing industry over other industries. A utility should consider proposing its preferred option to the public in advance in order to garner public support and answer any questions the public might have before implementing its preferred alternative.

MANAGERIAL IMPACTS

There are a number of managerial impacts to lime residuals management that need to be considered before making a decision on an alternative, including staffing requirements, funding sources, and challenges in bidding lime residuals to cement manufacturers.

Staffing Requirements

Each lime residuals disposal alternative would lead to hiring additional staff. Even the registered disposal site requires staff to haul residuals from the water treatment plant(s) to the registered disposal site, and both recalcination and beneficial reuse in cement manufacturing will require a larger staff increase than the registered disposal site. Utilities often have a limited number of budgeted positions available, so suddenly increasing staff size by 9-17 full time employees (FTEs) per year might be a challenge even for a large utility. Utilities should justify and budget for additional FTEs long before the FTEs need to begin working.

Funding Sources

Each of the lime residuals disposal alternatives creates capital and O&M costs. For example, the capital cost of recalcination is almost $39M. A utility choosing to recalcinate its residuals will either need to add the project to its Capital Improvements Plan (CIP) years in advance or have a bond election to borrow funds for the kiln.

Challenges in Bidding Lime Residuals to Cement Manufacturers

To beneficially reuse its lime residuals in cement manufacturing, a utility would need to contract with a cement manufacturer through the public bidding process. Even if the lime residuals could be offered for free, the utility would have to create a contractual system to determine which cement manufacturers receive the benefit of the free lime residuals, as well as the quantity received by each manufacturer, which would likely open the utility to additional public scrutiny and be subject to purchasing requirements. One option would be for a utility to solicit bids for the lime residuals and select the highest bidder (highest payer) rather than the lowest bidder. Alternatively, a utility could bid out the lime residuals and transportation (requiring the manufacturer to provide the transportation of the lime residuals) and select the lowest bidder from the bid pool. Any decision of how to bid the lime residuals to cement manufacturers is best left to the utility's purchasing group to ensure the bid process complies with the utility's policies.

REGULATORY REQUIREMENTS

Any selected lime residuals management alternative will need to be approved by the TCEQ and any utility-governing body. The utility should present its preferred alternative to the TCEQ and other appropriate governing bodies prior to moving forward with the selected alternative to ensure it will be approved.

Utility Values and Organizational Structure

Each utility has its own values, mission statement, and vision. Municipal utilities often have values that include customer affordability or environmental stewardship. Each utility ought to manage its lime residuals disposal in line with its values.

Large utilities or utilities that are part of a larger municipal government often have to answer to other governing bodies, such as a Council, Mayor, or Board of Directors. A utility might explore its options and select the best alternative for lime residuals management; however, if the utility staff's selection is not supported by its governing body, then it will not be approved for implementation. Any utility selecting a new lime residuals disposal alternative ought to communicate openly and often with its governing body to ensure support of its decision.

Chapter 5: Conclusions

This report evaluated the environmental and economic impacts associated with three lime residuals disposal alternatives: a registered disposal site, beneficially reusing the lime residuals in cement manufacturing, and recalcination. The registered disposal site was presented as a base case for cement manufacturing and recalcination because both alternatives benefit from allowing the residuals to air-dry at the registered disposal site.

The analyses presented in this report include a number of assumptions and simplifications because a number of impacts associated with lime residuals management alternatives are too site-specific to be relevant for a general-use report. Details such as the extent of magnesium pre-treatment required to recalcinate the residuals, the ability to capture carbon dioxide generated during recalcination, and the social cost of pollutants other than carbon dioxide might have significant impacts on the results of a utility's evaluation of its lime residuals management options.

This report found the emissions due to recalcination and the emissions reduction from beneficially reusing the lime residuals in cement manufacturing are orders of magnitude larger than the transportation emissions associated with the registered disposal site. While the emissions due to recalcination will likely be offset by a reduction in lime production and might not have any social impacts, some utilities will find shifting the emissions burden from the private sector to the public sector undesirable and therefore will not consider recalcination a viable alternative.

Of the three alternatives, recalcination has the highest capital costs due to the need to purchase a rotary kiln. Cement manufacturing has the highest operations and maintenance costs, and recalcination presents a net savings in operations and maintenance costs due to the chemical savings associated with reduced lime usage. Recalcination is the most financially attractive option, but cement manufacturing provides the most value when considering the social cost of carbon dioxide emissions.

Utilities should also consider non-economic factors when assessing lime residuals disposal alternatives. For example, while a registered disposal site is the simplest alternative evaluated in this report, both in cost and in maintenance, it is also temporary and may be seen as a short-term solution to a long-term problem. The kiln necessary for recalcination might be considered an eyesore to some, and beneficially reusing the lime residuals might be seen as giving the cement manufacturing industry an unfair advantage. Utilities should also consider managerial impacts associated with the preferred lime residuals alternative, such as the need for increased staff, potential sources of funding for capital costs, and challenges in bidding lime residuals to cement manufacturers. The selected alternative must also meet regulatory requirements, be in line with the utility's values, and be approved by any governing bodies such as a Council or Board of Directors. Ultimately, the best alternative for a utility will depend on that utility's specific parameters and priorities.

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